Mantle-melt Evolution (Dynamic Source) in the Origin of a Single MORB Suite: a Perspective from Magnesian Glasses of Macquarie Island

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The effects of source composition and source evolution during progressive partial melting on the chemistry of mantle-derived mid-ocean ridge basalt (MORB) melts were tested using a comprehensive geochemical and Sr–Nd–Pb isotopic dataset for fresh, magnesian basaltic glasses from the Miocene Macquarie Island ophiolite, SW Pacific. These glasses: (1) exhibit clear parent–daughter relationships; (2) allow simple reconstruction of primary melt compositions; (3) show exceptional compositional diversity (e.g. K_2O/TiO_2 0·09–0·9; La/Yb 1·5–22; $^{206}Pb/^{204}Pb$ 18·70–19·52); (4) preserve changes in major element and isotope compositions, which are correlated with the degree of trace element enrichment (e.g. La/Sm). Conventional models for MORB genesis invoke melting of mantle that is heterogeneous on a small scale, followed by binary mixing of variably lithophile element-enriched melt batches. This type of model fails to explain the compositions of the Macquarie Island glasses, principally because incompatible element ratios (e.g. Nb/U, Sr/Nd) and Pb isotope ratios vary non-systematically with the degree of enrichment. We propose that individual melt batches are produced from instantaneous 'parental' mantle parageneses, which change continuously as melting and melt extraction proceeds. This concept of a 'dynamic source' combines the models of small-scale mantle heterogeneities and fractional melting. A dynamic source is an assemblage of locally equilibrated mantle solids and a related melt fraction. Common MORB magmas that integrate the characteristics of numerous melt batches therefore tend to conceal the chemical and isotopic identity of a dynamic source. This study shows that isotope ratios of poorly mixed MORB melts are a complex function of the dynamic source evolution, and that the range in isotope ratios within a single MORB suite does not necessarily require mixing of diverse components.

INTRODUCTION

The heterogeneous nature of mid-ocean ridge basalts (MORB), the most voluminous type of volcanism on Earth, has been documented on both local and regional scales for the past three decades (e.g. Langmuir *et al.*, 1992). Variations among major, trace and volatile element, and radiogenic and stable isotopic compositions in MORB are believed to reflect the original variability of MORB primary magmas (i.e. equilibrated with mantle peridotite during melting). However, despite numerous empirical and experimental studies the compositions of MORB primary magmas remain controversial. Any particular MORB rock (or glass) appears to result from the mixing of different melt batches, and as such it may have numerous 'parents' (i.e. melts from which the resultant chemical characteristics are inherited). This conclusion is largely based on studies of melt inclusions within phenocrysts. For example, melt inclusions trapped in

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primitive phenocrysts (i.e. formed at the onset of crystallization from still unfractionated magmas) have provided convincing evidence for significant small-scale compositional variability of magmas. The melts represented by melt inclusions within a single suite vary in terms of major, trace and volatile elements (Sobolev & Shimizu, 1993; Nielsen *et al.*, 1994; Kamenetsky, 1996; McNeill & Danyushevsky, 1996; Sobolev, 1996; Sobolev & Chaussidon, 1996; Kamenetsky & Crawford, 1998; Kamenetsky *et al.*, 1998; Shimizu, 1998; Sours-Page *et al.*, 1999).

Processes invoked to explain the chemical diversity of primary melts include pressure and temperature variations during melting and melt extraction (e.g. Klein & Langmuir, 1987; Niu & Batiza, 1991; Kinzler & Grove, 1992; Langmuir *et al.*, 1992; Plank & Langmuir, 1992), and related changes in the extent of partial melting and permeability in the melting zone (e.g. Langmuir *et al.*, 1977; Maaloe, 1982; McKenzie, 1984; Sobolev & Shimizu, 1993). Primary melts, although maintaining equilibrium with mantle lithologies, may also experience irreversible changes en route to the surface through reaction with peridotites and via chromatographic effects (e.g. Navon & Stolper, 1987; Kelemen, 1990; Takazawa *et al.*, 1992; Hauri, 1997; Kelemen *et al.*, 1997; Kamenetsky & Crawford, 1998).

An alternative to process-related local variability in primary melts is pre-melting chemical heterogeneity of the mantle source regions, e.g. 'plum-pudding' or 'marble-cake' type upper-mantle models (e.g. Sleep, 1984; Allègre & Turcotte, 1986; Prinzhofer *et al.*, 1989). These mantle heterogeneities are assumed to have distinct trace element (e.g. enriched, fertile, depleted) and radiogenic isotope signatures, traditionally interpreted as indicators of long-term trace element enrichment or depletion of distinct mantle domains (see reviews by Zindler & Hart, 1986; Hofmann, 1997) However, as MORB are now known to integrate the characteristics of numerous melt fractions, the interpretation of isotopic data in terms of local mantle heterogeneity becomes problematic. This is illustrated by the large range of Pb isotope compositions found in melt inclusions from a single MORB suite (Shimizu, 1998).

In an attempt to distinguish between the effects of partial melting and initial source heterogeneity on the composition of MORB primary melts, and to further explore the concept of melting-induced evolution of a mantle source (termed 'dynamic source' in this paper), we present new isotope (Sr, Nd, Pb) data for a suite of very primitive melts (Group I glasses) and their fractionated counterparts (Group II glasses) from Macquarie Island, SW Pacific (Kamenetsky *et al.*, 2000). The primitive magnesian Group I glasses are characterized by exceptionally well-correlated major and trace element and isotopic compositions. We will show that the relations between trace element and isotope ratios in these glasses are inconsistent with simple binary mixing but may instead represent an example of a dynamic source, where the extent of melting is closely interrelated with the compositions of instantaneous melts.

MACQUARIE ISLAND GLASSES

The geological setting of the Miocene Macquarie Island ophiolite and the petrological–geochemical characteristics of basaltic glasses from the island have been described by Kamenetsky *et al.* (2000). Glasses from pillow lavas and hyaloclastites show variations in incompatible element ratios (e.g. K_2O/TiO_2 or La/Sm, Fig. 1) that are unusually large for any single MORB suite. The most lithophile element-enriched glasses have been inferred to represent a new extremely enriched end-member in the MORB compositional spectrum (Kamenetsky *et al.*, 2000). Two distinct types of glasses are recognized, which differ in terms of the degree of shallow-level fractionation (crystallization of olivine + spinel ± plagioclase ± clinopyroxene) of their parental melts. Near-primitive (Group I) glasses are distinguished from fractionated (Group II) glasses in having the highest Mg-number $[Mg/(Mg + Fe^{2+})]$, MgO, CaO and Al_2O_3 and the lowest FeO, TiO_2, Na_2O, K_2O and other incompatible element abundances at a given degree of enrichment (e.g. K_2O/TiO_2 or La/Sm, Fig. 2). A genetic relationship between Group I (parent) and Group II (derivative) has been demonstrated using major and trace element data (Kamenetsky *et al.*, 2000). Calculated primary melt compositions in equilibrium with the most primitive Macquarie Island olivine phenocrysts $Fo_{90.5}$ (Kamenetsky *et al.*, 2000) parallel the compositions of Group I glasses at higher (by ∼3 wt %) MgO (Fig. 2). The continuous change in primary melt compositions has been ascribed to an increasing degree of partial melting of a mantle source that was homogeneous on a large scale (Kamenetsky *et al.*, 2000).

PROCEDURES FOR Nd–Sr–Pb ISOTOPE ANALYSES AND AGE CORRECTIONS

Unaltered glass fragments (100–250 mg) were leached for 1 h in hot 6M HCl, rinsed with water, and dissolved in open beakers using HF–HNO_3 and HCl. Pb was separated first, following techniques described by Manhes *et al.* (1978). The Pb-free eluate was then processed over 0·15 ml Sr.spec and TRU.spec columns to purify Sr and a fraction containing the light rare earth elements (LREE), respectively, following methods modified from Pin *et*
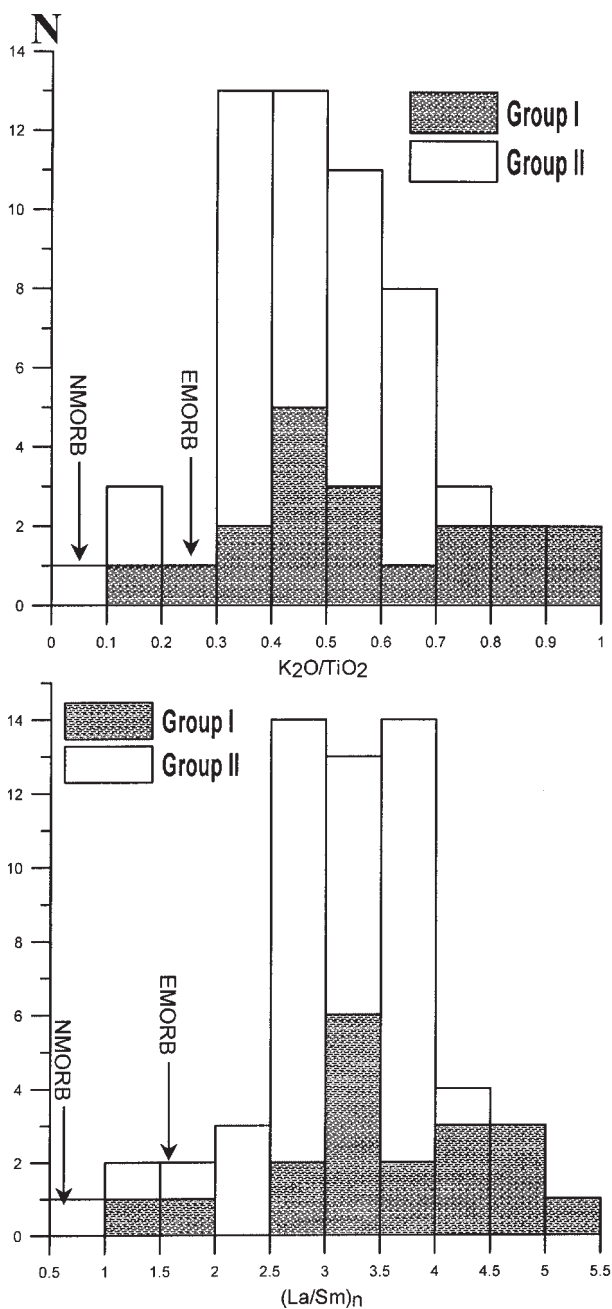
Fig. 1. Distribution of K_2O/TiO_2 and $(La/Sm)_n$ values [subscript n indicates normalization to primitive mantle values of Sun & McDonough (1989)] in near-primitive (Group I, $N = 19$) and fractionated (Group II, $N = 38$) glasses from the Macquarie Island ophiolite. The compositions of typical depleted (NMORB) and enriched (EMORB) mid-ocean ridge basalts (Sun & McDonough, 1989) are indicated by arrows.

tween resin batches. Nd was further purified on 3 ml beds of HDEHP-coated Kel-F material (Richard *et al.*, 1976). Isotopic analyses were carried out on a Finnigan-MAT262 multicollector instrument at La Trobe University in static multicollection mode. Instrumental mass fractionation was corrected by normalizing to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. All analyses are reported relative to SRM987-Sr $= 0.71023$ and La Jolla-Nd $= 0.511860$. Sr–Nd isotope data for six Macquarie Island glasses reported by Kamenetsky *et al.* (2000) were readjusted to be compatible with these standard results. Samples 38287 and 47963 of Kamenetsky *et al.* (2000) were reanalysed and yielded Sr–Nd isotope ratios within analytical errors of the results reported earlier. Analytical errors are taken to be equal to external (2σ pop) precisions obtained for multiple runs of standards: ± 0.000030 (Sr) and ± 0.000020 (Nd).

Lead was analysed using the Si-gel method (Gerstenberger & Haase, 1997) and mass fractionation was controlled with a ^{204}Pb–^{207}Pb double spike (Woodhead *et al.*, 1995). Samples were split just before filament loading, and spike was added to the ID-aliquot on the filament, avoiding potential contamination of Teflon labware with the spike. The double-spike technique can reduce analytical errors to below $\pm 0.05\%$ (2σ pop) for well-spiked samples. All our spiked Pb runs had Q-values around 0.1, i.e. within the low error propagation range of Manhes *et al.* (1978) and should therefore be highly precise. This is confirmed by the results of full repeat dissolutions. Total Pb blanks were <150 pg and are negligible relative to estimated minimum sample sizes of ~ 100 ng.

Age corrections (for an age of 11 Ma, Varne *et al.*, 2001) were applied to all isotopic results. For Nd and Sr these corrections were negligible. Age corrections to Pb isotope ratios were always less than 0.4% and 0.1% for $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, respectively. Although this is in excess of analytical precision, the consequences for geochemical interpretations are negligible.

RESULTS

The nine Group I glasses selected for isotope (Sr, Nd, and Pb) analysis represent the entire range of near-primitive compositions from highly enriched [sample 47963, $(La/Sm)_n = 5.1$, where subscript n indicates normalization to primitive mantle values of Sun & McDonough (1989)] to moderately enriched [sample 47979, $(La/Sm)_n = 1.3$]. This range is extended to moderately depleted compositions by inclusion of two Group II glasses [samples G452a and HP135 with $(La/Sm)_n = 0.9$ and 1.2, respectively], which have no primitive counterparts among Group I glasses. In addition, five moderately enriched Group II glasses [$(La/Sm)_n = 2.2–2.7$] showing different degrees of crystal fractionation
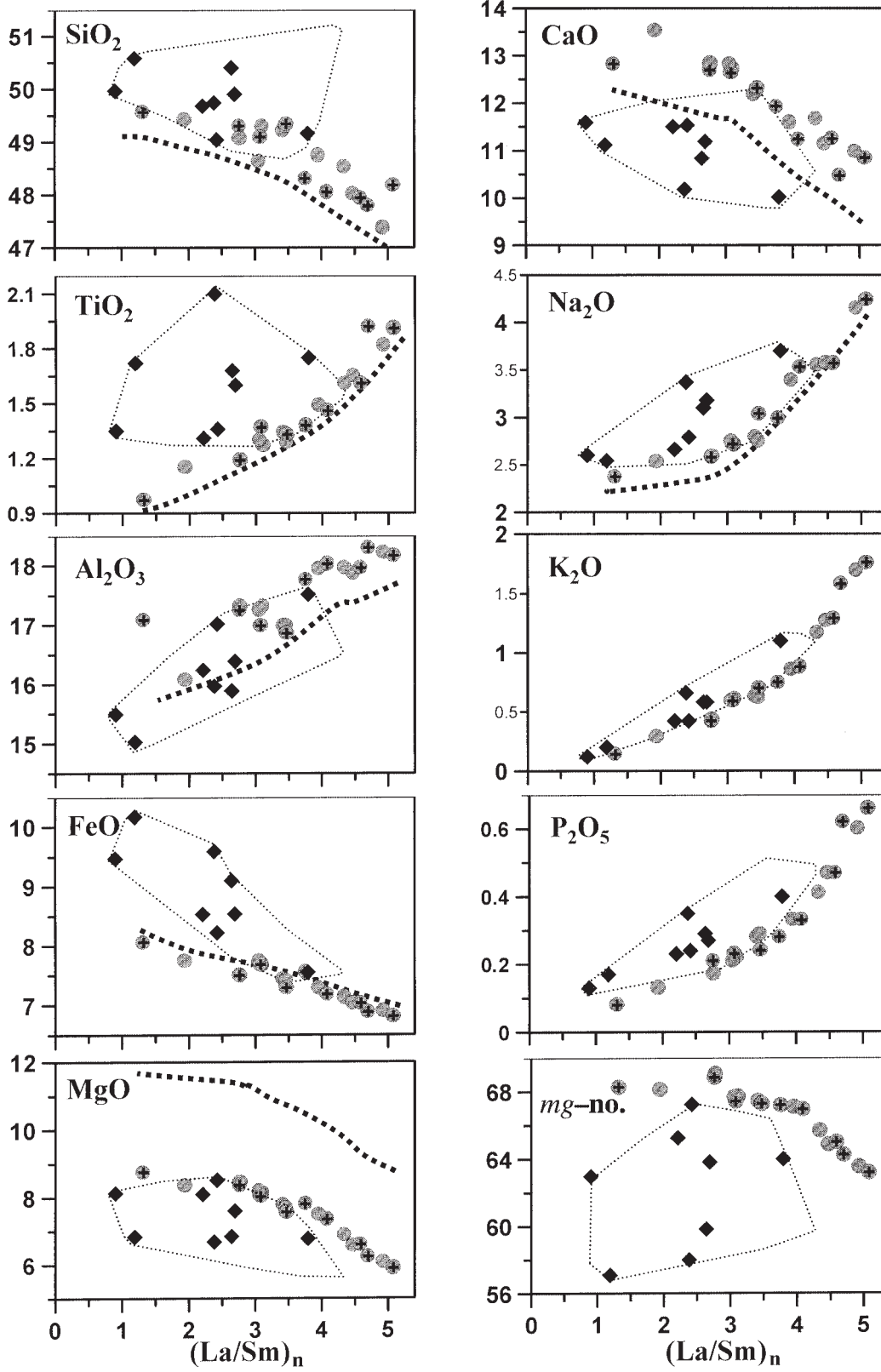
al. (1994). Column blanks measured for these element-specific resins were considerably lower (<40 pg of Sr, <10 pg of Nd) than indicated by Pin *et al.* (1994), suggesting there may be drastic memory variations be-

Table 1: Major (in wt %) and selected trace (in ppm) element composition and isotope (Sr, Nd and Pb) ratios of the Macquarie Island glasses

Sample:	Group I (near-primitive) glasses								
	47979	25637	60701	GG53a	G855	GG256	G882b	78	47963
$^{87}Sr/^{86}Sr$	0·702572	0·702635	0·702675	0·702672	0·702906	0·702684	0·702761	0·703336	0·702764
$^{143}Nd/^{144}Nd$	0·513063	0·513058	0·513003	0·513032	0·513029	0·513014	0·513001	0·513003	0·513013
$^{206}Pb/^{204}Pb$	18·951	19·384	19·446	19·487	19·499	19·517	19·441	19·41	19·493
$^{207}Pb/^{204}Pb$	15·528	15·562	15·584	15·572	15·579	15·591	15·578	15·574	15·589
$^{208}Pb/^{204}Pb$	38·523	38·876	38·966	38·976	38·991	39·029	38·944	38·927	38·979
SiO_2	49·56	49·30	49·09	49·34	48·31	48·05	47·94	47·79	48·18
TiO_2	0·97	1·19	1·37	1·33	1·38	1·46	1·61	1·92	1·91
Al_2O_3	17·09	17·25	16·99	16·86	17·77	18·03	17·96	18·30	18·17
FeO	8·06	7·50	7·68	7·29	7·55	7·18	7·03	6·88	6·81
MnO	0·14	0·17	0·12	0·12	0·14	0·07	0·09	0·12	0·08
MgO	8·75	8·36	8·02	7·56	7·80	7·34	6·59	6·24	5·90
CaO	12·82	12·69	12·63	12·31	11·93	11·24	11·25	10·47	10·85
Na_2O	2·37	2·58	2·72	3·04	2·99	3·53	3·57	variable*	4·24
K_2O	0·14	0·42	0·59	0·70	0·75	0·88	1·29	1·58	1·76
P_2O_5	0·08	0·21	0·23	0·24	0·28	0·33	0·47	0·62	0·66
Total	99·98	99·67	99·44	98·79	98·90	98·11	97·80	variable*	98·56
Mg-no.	68·3	68·8	67·4	67·3	67·2	66·9	65·0	64·2	63·2
Rb	3·60	13·3	19·4	23·3	24·5	30·9	44·9		59·5
Sr	155	246	290	316	335	397	555		703
Nd	7·57	13·3	15·3	17·8	17·8	21·0	26·9		33·0
Sm	2·26	3·12	3·47	3·87	3·72	4·19	5·04		5·93
Pb	0·503	0·971	1·13	1·34	1·39	1·69	2·22		2·89
Th	0·494	1·83	2·25	3·10	3·18	4·06	5·26		7·04
U	0·155	0·484	0·648	0·808	0·855	1·13	1·39		1·94
Yb	1·98	2·11	2·12	2·34	2·23	2·39	2·16		2·13
La/Sm	2·05	4·27	4·76	5·37	5·80	6·31	7·11	7·30†	7·86

($\sim$10–45%) from Group I precursors, were analysed to check if crystal fractionation was accompanied by isotopic changes. Furthermore, one Group II glass [sample 25601, $(La/Sm)_n = 3·8$] was analysed as an example of the strongly enriched compositions in this group. The isotopic data together with major element compositions and selected trace elements are presented in Table 1 and shown in Figs 3 and 4.

Isotope ratios of Pb and Nd show positive hyperbolic and negative linear correlations, respectively, with the degree of enrichment, as represented by La/Sm (Fig. 3). It should be noted that the measured variation in Nd isotopes is less than twice the external precision; nevertheless a clear correlation ($R = 0·85$) is observed with the degree of enrichment (Fig. 3).

Strontium isotope data have considerable scatter at a given La/Sm (Fig. 3). For example, glass 78 (Group I) has much higher $^{87}Sr/^{86}Sr$ (0·70334) than other near-primitive glasses (0·70257–0·70291). This fresh-looking glass also exhibits significant dispersion of Na_2O (1·9–

Fig. 2. Correlations between $(La/Sm)_n$ and major elements (in wt %), and Mg-number [$Mg/(Mg + 0·9Fe^{total})$], in mol %) in Macquarie Island glasses (grey circles, Group I glasses; field indicates Group II glasses). Samples analysed for isotopes [this work and Kamenetsky *et al.* (2000)] are shown by + (Group I) and ◆ (Group II). Calculated compositions of near-primary melts are represented by the bold dotted line. Near-primary melts were calculated from Group I glasses by addition of olivine to achieve equilibrium with $Fo_{90·5}$, the most primitive olivine found in Macquarie Island extrusive rocks (Kamenetsky *et al.*, 2000).

	Group II (fractionated) glasses							
Sample:	G452a	HP135	G565a	38287	G465	40428	G955b	25601
$^{87}Sr/^{86}Sr$	0·702797	0·702739	0·70312	0·702657	0·703287	0·702621	0·702663	0·702769
$^{143}Nd/^{144}Nd$	0·513052	0·513063	0·513051	0·513034	0·513050	0·51304	0·513044	0·513024
$^{206}Pb/^{204}Pb$	18·704	18·948	19·108	19·268	19·332	19·376	19·337	19·294
$^{207}Pb/^{204}Pb$	15·495	15·527	15·539	15·554	15·557	15·569	15·567	15·565
$^{208}Pb/^{204}Pb$	38·286	38·519	38·634	38·806	38·819	38·903	38·870	38·808
SiO_2	49·96	50·58	49·68	49·74	49·04	50·40	49·90	49·16
TiO_2	1·35	1·72	1·31	2·10	1·36	1·68	1·60	1·75
Al_2O_3	15·49	15·03	16·24	15·97	17·02	15·89	16·39	17·52
FeO	9·47	10·17	8·53	9·59	8·22	9·10	8·54	7·55
MnO	0·13	0·18	0·12	0·17	0·12	0·16	0·17	0·15
MgO	8·13	6·83	8·09	6·68	8·51	6·84	7·60	6·77
CaO	11·59	11·12	11·50	10·18	11·53	10·84	11·19	10·02
Na_2O	2·60	2·54	2·66	3·37	2·79	3·10	3·18	3·70
K_2O	0·12	0·20	0·42	0·66	0·42	0·58	0·58	1·10
P_2O_5	0·13	0·17	0·23	0·35	0·24	0·29	0·27	0·40
Total	98·97	98·54	98·78	98·81	99·25	98·88	99·42	98·12
Mg-no.	63·0	57·1	65·3	58·0	67·2	59·8	63·8	64·0
Rb	3·2	6·1	12·3	22·0	13·9	23·2	19·5	36·7
Sr	111	141	227	225	240	215	252	443
Nd	9·53	13·7	13·4	23·1	13·7	20·3	17·4	23·9
Sm	3·10	4·11	3·30	5·69	3·36	4·81	4·09	4·89
Pb	0·504	0·709	1·006	1·43	0·973	1·41	1·27	2·02
Th	0·427	0·833	1·40	2·92	1·63	2·93	2·40	4·21
U	0·127	0·225	0·409	0·779	0·508	0·742	0·698	1·24
Yb	2·92	3·70	2·36	4·03	2·36	3·38	2·70	2·47
La/Sm	1·40	1·84	3·42	3·69	3·75	4·08	4·16	5·87

*Na_2O content and the total of the microprobe analyses of glass 78 vary possibly because of alteration (see text for details).
†La/Sm in glass 78 is calculated from the correlation between K_2O/TiO_2 and La/Sm in other Macquarie Island glasses.
Mg-no. is $100Mg/(Mg + 0.9Fe^{total})$, in mol %.

3·7 wt %) and strong covariation of Na_2O with the total of the microprobe analysis (96·8–100·8 wt %, $R = 0.96$), whereas other major element oxides remain constant (Table 1). This can be explained by patchy alteration along cracks and diffusion of some elements (e.g. Na and Sr) during interaction with seawater. Therefore, we assume that glasses with the lowest $^{87}Sr/^{86}Sr$ at a given La/Sm may represent a linear trend of truly magmatic values for $^{87}Sr/^{86}Sr$ (shown in Fig. 3). By inference, any composition above this line is interpreted as a result of exchange with or contamination by seawater. The outliers from the 'magmatic trend' are four Group II glasses (samples G452a, HP135, G565a and G465) and another Group I glass, G855, although none of them show dispersion in Na_2O.

In general, Macquarie Island glasses have isotopic compositions indistinguishable from typical MORB and extend over approximately half of the total Pb isotopic range found in Pacific MORB (Fig. 4). There is no systematic isotopic difference between near-primitive and fractionated glasses, which confirms that isotope compositions remained unchanged during crystallization. We can therefore use all studied glasses to isotopically characterize their parental, more primitive melts.

ORIGIN OF MACQUARIE ISLAND PRIMARY MELTS

As pointed out above, we believe that one of the principal reasons for the problems encountered in constraining prim-
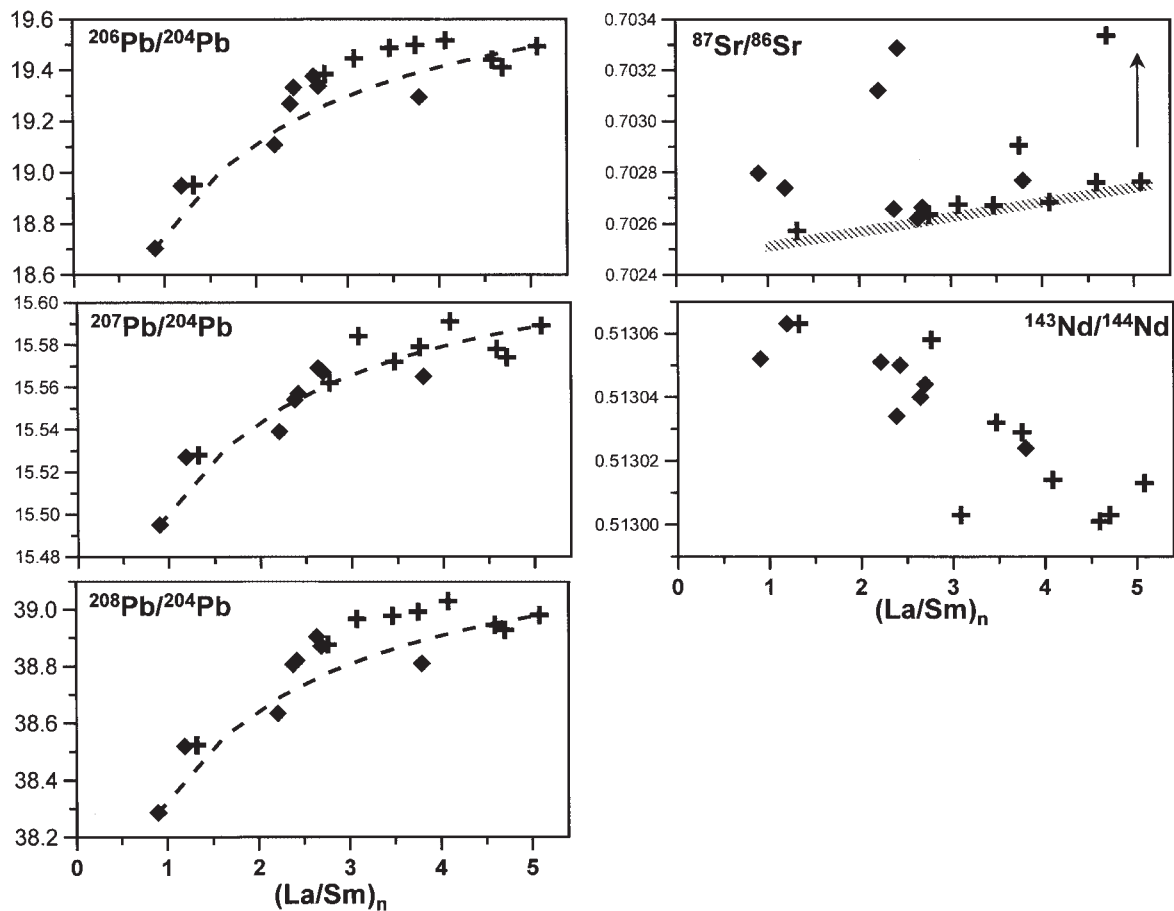
Fig. 3. Covariation of $(La/Sm)_n$ and isotope (Pb, Sr and Nd) ratios in Macquarie Island glasses. Symbols as in Fig. 2. Dashed lines on Pb isotope plots show hypothetical binary mixing between most enriched (sample 47963) and most depleted (sample G452a) compositions (Table 1). A diagonally shaded line and an arrow on the Sr isotope plot show possible magmatic (pre-alteration) values and changes as a result of exchange with seawater, respectively.

ary melt composition(s) for a given MORB suite is the similarity of the effects produced by mixing of primary melts and those produced by partial melting. Even binary mixing of primary melts gives rise to a melt that is not primary, and as such cannot be used to characterize mantle compositions and processes. However, we will argue below that the spectrum of Macquarie Island glass compositions is not a product of mixing of melts, as is commonly assumed for many diverse MORB suites. This implies that those of the glasses' geochemical parameters that remained unaffected by crystal fractionation (e.g. isotope ratios and certain trace element ratios) were inherited from the hypothetical primary melts, and thus represent the characteristics of the mantle source(s). We propose a scenario in which major and trace elemental and isotopic variations in primary melts reflect gradually increasing degrees of melting, leading to instantaneous change in the source mineralogical and chemical composition. In other words, we imply that each primary melt batch has its own source.

Source vs melting: trace element evidence

The origin of enriched MOR magmas (e.g. EMORB) requires either very small degrees of partial melting or a mantle source that is relatively enriched in incompatible trace elements, or both (e.g. Langmuir *et al.*, 1977; le Roex, 1987; le Roex *et al.*, 1989, 1992; Natland, 1989; Allan *et al.*, 1993; Niu *et al.*, 1996, 1999; Shimizu, 1998; Kamenetsky *et al.*, 2000). Alternatively, EMORB as a distinct type may be interpreted as a mixture between depleted magmas (NMORB) and melts that are even more enriched than typical EMORB. A possible candidate for such a highly enriched end-member can be found among the most enriched [$(La/Sm)_n = 5$, La 45 ppm] primitive melts from Macquarie Island (Kamenetsky *et al.*, 2000). However, simple binary mixing of the most enriched and depleted compositions (e.g. samples 47963 and 47979, respectively, Table 1) cannot satisfactorily explain the entire compositional range of
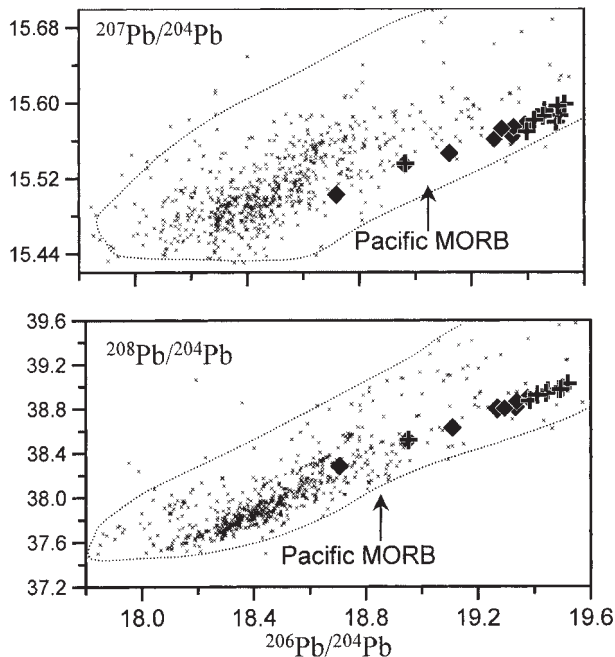
Fig. 4. Lead isotope variations in Macquarie Island glasses compared with Pacific MORB global array (small ×, numerous sources). Symbols as in Fig. 2.

Macquarie Island primitive melts. For example, binary mixing is inconsistent with the non-systematic change in the ratios of trace elements (e.g. Nb/U, Ce/Pb, Sr/Nd, Zr/Sm; see Fig. 5a–d) that are considered to have near-similar incompatibility during melting (e.g. Sun & McDonough, 1989). We assume, therefore, that the trend from extremely enriched melts to varieties showing no enrichment [e.g. $(La/Sm)_n = 1$, La 5 ppm] or even to highly depleted melts (such as those represented by some glasses from the East Pacific Rise seamounts with $(La/Sm)_n = 0.4$ and 1 ppm La; Niu & Batiza, 1997), illustrated here for Nb/U and Ce/Pb (Fig. 5e and f), is not produced by binary mixing, but is instead controlled by melting and changes in the source composition.

Melting (increasing degree of melting, F) and the 'dynamic' (changing) composition of a source undergoing melting are interrelated. Melting starts (low F) in a mantle lithology with a relatively low solidus temperature, i.e. richest in fusible components or phases. Segregation and extraction of low-F melts leaves a residue that produces melts of different (less enriched) composition upon further melting (higher F). Inflections in the trends of incompatible element ratios such as observed here (Fig. 5; see also Niu & Batiza, 1997; Danyushevsky et al., 2000) can be caused by melting-induced changes in the mineralogical and chemical composition of the source.

To illustrate the effects of the source, we compare trace element ratios in the Macquarie Island glasses and

various MORB suites (Fig. 6). Gd/Yb is used to monitor F during melting of a garnet-free source, whereas La/Ce is employed as an indicator of incompatible element enrichment of melts produced during the melting or inherited from an enriched source. At comparable degrees of melting (similar Gd/Yb), Macquarie Island glasses have systematically higher La/Ce than MORB worldwide, presumably because they originate from a source more enriched in highly incompatible elements than the source of typical MORB. In both MORB and Macquarie Island glasses, melting and pre-melting enrichment of the source appear to be decoupled, i.e. the enrichment is not a cause of melting (although enriched mantle lithologies may melt preferentially). This decoupling is deduced from comparison with a basalt suite from the Troodos ophiolite (Fig. 6), which is inferred to originate from a mantle source modified by addition of enriched components before and during melting in a supra-subduction environment (e.g. Cameron, 1985). Compositions of these Troodos basaltic glasses range from moderately depleted [Gd/Yb ∼1·15–1·25, rare earth elements (REE) ∼(2–3) × PM (primitive mantle)] NMORB-like compositions and evolve towards very low Gd/Yb (0·45) with extreme depletion in LREE and middle REE (MREE) (<1 × PM), but very high La/Ce (up to 0·58) according to Portnyagin (1997). High La/Ce in strongly LREE-depleted basalts must reflect addition of LREE-enriched fluxing agents (e.g. a melt with high La/Ce) to a mantle source that has been progressively depleted as a result of contemporaneous melting.

Uncommon nature of enriched melts: 'filtering' effects in the conduit

If, as assumed above, generation of enriched to depleted MORB melts occurs in a continuous melting process, the enriched melts must form early, whereas less enriched melts will form later. To be erupted, the early enriched melts need to segregate and then establish, fill and 'overfill' the conduit (plumbing system). While these melts create a volcanic conduit and lose their trace element signature as a result of re-equilibration with depleted upper mantle, melting in the source continues to produce more voluminous and less enriched (ultimately, depleted) melts (Fig. 6). This scenario may explain the rarity of enriched compositions among erupted MORB and their common occurrence among melt inclusions trapped in primitive MORB phenocrysts (e.g. Kamenetsky, 1996; Sobolev, 1996; Tsamerian & Sobolev, 1996; Kamenetsky et al., 1998; Shimizu, 1998). A unique feature of the Macquarie Island MORB suite—the predominance of enriched varieties and an absence of fractionated counterparts for the most enriched melts (Fig. 1)—provides evidence that early magma batches erupted with little or
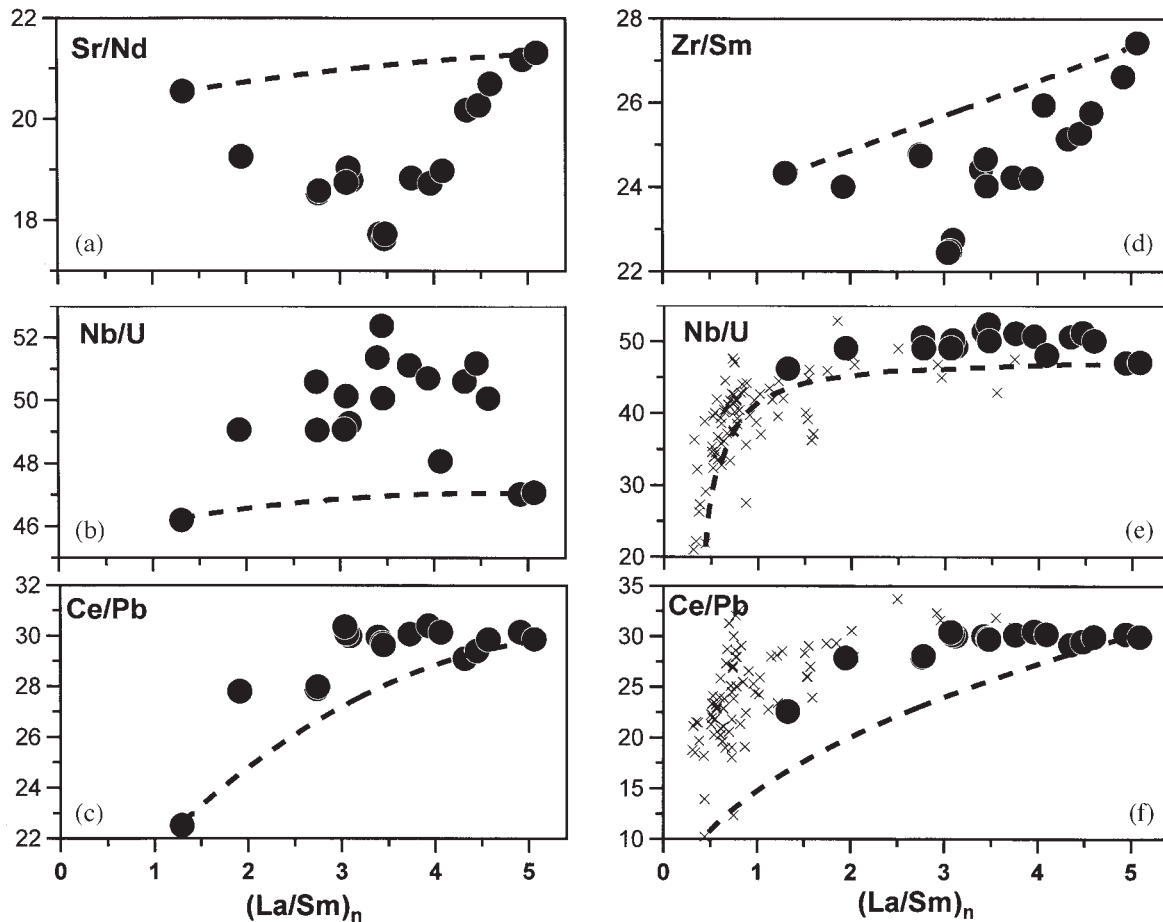
Fig. 5. $(La/Sm)_n$ vs ratios of trace elements of near-equal incompatibility [according to Sun & McDonough (1989)] during partial mantle melting in Macquarie Island Group I glasses. Dashed lines show hypothetical binary mixing between: (a–d) most enriched (sample 47963) and most depleted (sample G452a) Group I compositions from this study, and (e, f) most enriched (sample 47963) Group I Macquarie Island glass and most depleted composition among basalts from the East Pacific Rise seamounts ($\times$, Niu & Batiza, 1997). It should be noted that only the compositions unaffected by plagioclase crystallization [which increases Zr/Sm and decreases Sr/Nd over primary values; Kamenetsky et al. (2000)] are used.

no mixing and fractionation, possibly because the magma chamber was transient and narrow, if ever present. Eruption of very unusual magmas, although exceptionally rare, does occur in some mid-ocean ridge environments (e.g. le Roex et al., 1992; Allan et al., 1993; Klein & Karsten, 1995; Kamenetsky et al., 2001), and the oceanic crust of Macquarie Island created at the Australia–Pacific plate boundary within a slow-spreading, waning system (Varne et al., 2001) was such a site.

Source vs melting: major element evidence

Our interpretation of the data for Macquarie Island magnesian glasses provides an alternative to models that infer that enriched and depleted MORB with broadly similar major element compositions originate from similar degrees of melting of different, variably enriched or depleted sources (e.g. Lundstrom et al., 2000). In fact, the melting-induced source evolution thought here to have produced variable trace element compositions can also explain the observed trends in major element composition in the Macquarie Island primary melts (Fig. 2). These trends partly coincide with or parallel the trends of 1·5–2·0 GPa experimental melts from fertile peridotites [review by Varne et al. (2001)]. However, unusually low FeO and high Na_2O coupled with extreme trace element abundances in the enriched Macquarie Island primary melts probably require clinopyroxene-rich lithologies in the mantle source, as has been proposed in this case (Varne et al., 2001) and for some other MORB suites (e.g. Prinzhofer et al., 1989; Langmuir et al., 1992; Hirschmann & Stolper, 1996; Kamenetsky et al., 1998).
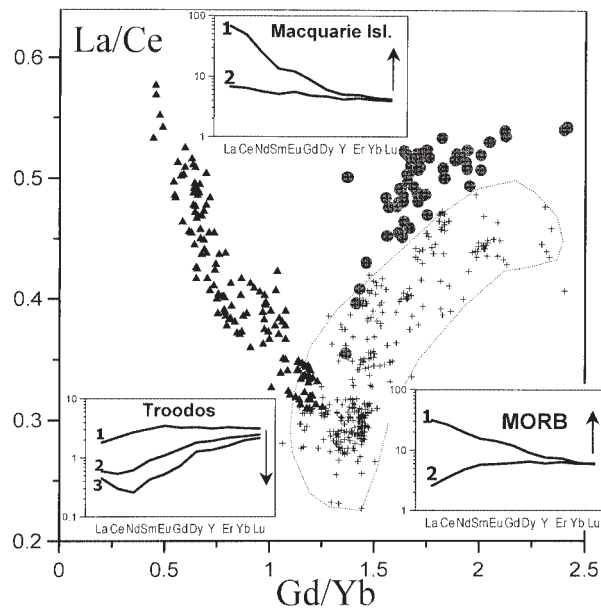
Fig. 6. Correlations between Gd/Yb and La/Ce ratios in glasses from Macquarie Island ophiolite (grey circles), mid-ocean ridges (+, from numerous sources) and Troodos ophiolite (▲, Portnyagin, 1997, and unpublished data, 1996). Insets show primitive mantle-normalized (Sun & McDonough, 1989) rare-earth element + yttrium patterns for selected compositions (numbered on the spidergrams and represented in the table below) with contrasting Gd/Yb and La/Ce ratios. Arrows indicate increasing La/Ce.

	Macquarie Island		MORB		Troodos, Cyprus		
	1	2	1	2	1	2	3
Gd/Yb	2·40	1·43	2·34	1·23	1·22	0·74	0·45
La/Ce	0·54	0·41	0·46	0·28	0·31	0·43	0·58

These predictions are supported by the experiments of Pickering-Witter & Johnston (2000), who studied the melts produced by melting of fertile peridotites with unusually high clinopyroxene modes (up to 40%). Major element trends in these experimental melts are broadly consistent with those observed in the Macquarie Island primary melts. This suggests that clinopyroxene-rich source lithologies may exert a strong control on major (and trace) elements at low-F melting, and a much diminished role at higher F. However, these constraints remain somewhat inconclusive without support from radiogenic isotopes, which are traditionally considered the best tool to distinguish between the effects of source composition and melting.

Origin of isotopic signature in magmas

The isotopic signature of any MORB suite integrates the isotopic compositions of individual melt fractions (e.g. Shimizu *et al.*, 1998). The isotopic ratios of a melt will reflect the source characteristics only if re-equilibration with isotopically distinct mantle lithologies or other melts is unimportant. Because re-equilibration in a molten environment is fast (Hofmann & Hart, 1978), preservation of the source isotopic signature would require a source volume larger than the melt generation volume. When the melt generation volume is larger than the isotopically distinct mantle domain, a primary melt would acquire a 'mixed' signature. Such 'mixed' signatures have given rise to the concept of mantle heterogeneities [reviews by Hofmann & Hart (1978), Sleep (1984) and Zindler & Hart (1986)].

Regional-scale isotopic differences in MORB are believed to represent large-scale mantle heterogeneities, i.e. distinct mantle domains (e.g. Hart, 1984; Hamelin & Allègre, 1985; Schilling, 1986; Ito *et al.*, 1987; Mahoney *et al.*, 1989; Pyle *et al.*, 1992; Fontignie & Schilling, 1996), whereas isotopic variations among MORB erupted within certain rift segments, in fracture zones, or on rift-related seamounts, have been attributed to smaller-scale mantle

heterogeneities. Popular models of small-scale mantle heterogeneity, such as 'marble-cake mantle' (e.g. Allègre & Turcotte, 1986; Prinzhofer *et al.*, 1989), 'veined mantle' (e.g. Wood, 1979), or the 'ubiquitous mantle hetero-geneities' of Sleep (1984), envisaged heterogeneities to be as small as a 'bread box'. Recent experimental data on REE diffusion rates in pyroxene at upper-mantle conditions (Van Orman *et al.*, 2001) suggest that isotopic heterogeneities on a scale as small as single grains may be viable.

Isotopic variation in a series of primary melts requires isotopically distinct components in the source, in some cases perhaps in the form of individual grains as suggested above. Whatever the form of the heterogeneities, the standard interpretation of trace element and isotopic trends in a single MORB suite is to regard them as a result of mixing of hypothetical end-member compositions. At least in the case of the Macquarie Island glasses, such a mixing model fails to match the observed isotopic and chemical trends (Figs 3 and 5), and the standard melt mixing model therefore appears inappropriate. We suggest that production and extraction of primary melts at a progressively increasing degree of melting with a complementary evolution of the source provides a better explanation.

Fig. 7. Correlations between Nd/Sm and Pb and Nd isotope ratios in glasses from Macquarie Island (●) and basalts from DSDP–ODP Hole 504B, Costa Rica Rift (×, Pedersen & Furnes, 2001). An axis with corresponding $(La/Sm)_n$ values in Macquarie Island glasses is shown.

Dynamic source: reconciliation between source and melting effects

At this point in our discussion we prefer to abandon the term 'heterogeneity' (although isotope heterogeneity is real) because the actual size and form of the mantle lithology responsible for a discrete melt is impossible to quantify. In fact, any source phase assemblage is heterogeneous in terms of isotopic composition before melting as each mantle phase has developed a distinct isotopic composition (e.g. Sigvaldason *et al.*, 1974; Mineyev *et al.*, 1992; Van Orman *et al.*, 2001) depending on its initial trace element composition, time of isolation, and the rate of diffusive re-equilibration with neighbouring phases. Therefore, we adopt the idea of 'local equilibrium between each melt and the local phase assemblage(s) that undergoes melting' (Phipps Morgan, 1999), which assumes that mantle melts leave their residua rapidly enough to escape re-equilibration with the larger mantle volume. Accordingly, we introduce a new term, 'dynamic source', to substitute for the ambiguous 'heterogeneity'. A dynamic source is any instantaneous mantle + melt assemblage that changes continuously through fractional melting and incomplete melt removal. Importantly, in this definition we presume that the size and shape of the dynamic source are also dynamic, i.e. increasing and changing, respectively, with melting.

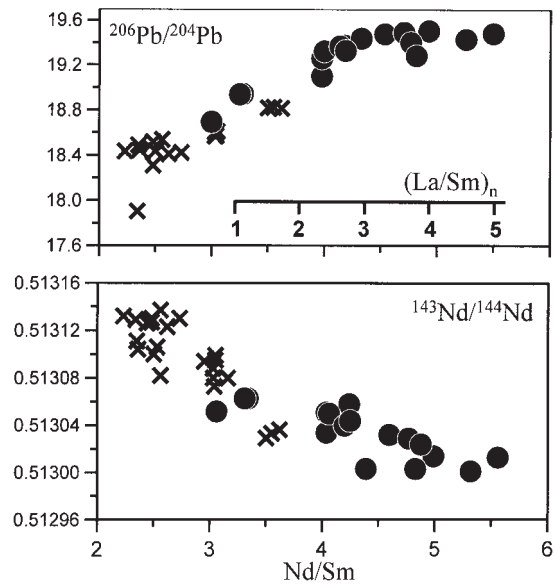Each melt composition erupted without mixing and crystallization is a snapshot of the dynamic source. The

evolution of a dynamic source may be illustrated by using our Macquarie Island glasses as an example. La/Sm is chosen here as an instantaneous characteristic of the dynamic source because these two elements are coupled in all source compositions and during partial melting. The general correlation between La/Sm, high Pb–Sr and low Nd isotope ratios (Fig. 3) indicates that high La/Sm is an inherent feature (enrichment; see also Fig. 6) of the dynamic source before and at the onset of melting. The change in Pb and Nd isotope ratios with increasing degree of melting (lower La/Sm) becomes even more pronounced if the Macquarie Island data are augmented with data for a depleted basaltic suite from the Deep Sea Drilling Project (DSDP)–Ocean Drilling Program (ODP) Hole 504B, Costa Rica Rift (Pedersen & Furnes, 2001). This is shown in Fig. 7, where Nd/Sm is used as a proxy for La/Sm (La concentrations for Hole 504B basalts were not available to us). Fractional melting and depletion in the dynamic source result in decreasing La/Sm in the partial melts. Fractionation of La/Sm, highest at the onset of melting (low-F melt fractions), is not accompanied by a change in Pb isotope ratios (Figs 3 and 7). Once the dynamic source evolves to the point at which melts with $(La/Sm)_n$ <3 (Nd/Sm <4·5) are produced, the change in Pb isotope ratios is dramatic (e.g. $^{206}Pb/^{204}Pb$ from 19·4 to 18·7 in the Macquarie Island glasses, and to 17·9 in the Hole 504B basalts, Fig. 7). Like the Pb isotopes, change in Nd isotope ratios is

more pronounced for less enriched and depleted compositions (Fig. 7).

The major change in the dynamic source composition, recorded in Pb isotopes at $(La/Sm)_n \sim 3$, is also evident in the trends of some trace element ratios (Fig. 5). One possible explanation involves fluctuations in relative incompatibilities (bulk K_d) of trace elements during melting, depending on the types of phases entering or disappearing from the dynamic source, their relative proportions, and their instantaneous chemical composition.

The further extension of the MORB database with truly primary or near-primary compositions will show whether the dynamic source concept in conjunction with the MET model (Melt Extraction Trajectories; Phipps Morgan, 1999) is ready to substitute for conventional two-component mixing. In this regard, particular effort should go towards the documentation of isotopic diversity in coexisting melts as sampled by melt inclusions in MORB and OIB (e.g. Saal *et al.*, 1998; Shimizu *et al.*, 1998).

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